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Thermal Modeling of A Friction Bonding Process

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Abstract: A COMSOL model capable of predicting temperature evolution during nuclear fuel fabrication is being developed at the Idaho National Laboratory (INL). Fuel plates are fabricated by friction bonding (FB) uranium-molybdenum (U-Mo) alloy foils positioned between two aluminum plates. The ability to predict temperature distribution during fabrication is imperative to ensure good quality bonding without inducing an undesirable chemical reaction between U-Mo and aluminum. A three-dimensional heat transfer model of the FB process implementing shallow pin penetration for cladding monolithic nuclear fuel foils is presented. Temperature distribution during the FB process as a function of fabrication parameters such as weld speed, tool load, and tool rotational frequency are predicted. Model assumptions, settings, and equations are described in relation to standard friction stir welding. Current experimental design for validation and calibration of the model is also demonstrated. Resulting experimental data reveal the accuracy in describing asymmetrical temperature distributions about the tool face. Temperature of the bonded plate drops beneath the pin and is higher on the advancing side than the retreating side of the tool.

Keywords: Friction Bonding, Friction Stir Welding, Thermal Modeling, Nuclear Fuels

1. Introduction

A model was created as a means to understand the thermal aspects of a unique friction bonding (FB) process developed at the Idaho National Laboratory (INL) as part of the Reduced Enrichment for Research and Test Reactors (RERTR) program [1-5]. The process is used for cladding low-enriched uranium (LEU) monolithic fuel alloys with aluminum for fuel plate fabrication. Two thin aluminum plates are bonded together, one above the other, with a monolithic Uranium-Molybdenum (U-Mo) alloy between them. In this manner, a thin foil of fuel can be shielded against corrosion in a compact

sheet. The methods for bonding currently under consideration include both hot isostatic pressing (HIP) and friction bonding (FB). FB is potentially a large-scale production technique, but there are challenges associated with the quality of the Al to U-Mo bond and the effects of the stirring motion above the U-Mo foil.

The FB approach is similar to a lap joint except that two entire plates are bonded (not just an overlapping edge) and several parallel passes are required, on both sides of the pieces being joined. It also uses a short pin with minimal stirring motion to avoid disturbing the U-Mo monolith. The INL FB process is therefore unlike many industrial and academic friction stir welding (FSW) processes that tend to maximize stirring to accomplish single-pass butt welds. Given these differences, it has proven insufficient to simply translate standard operating parameters to the INL process and expect standard results. The over-reaching purpose of the model is to experiment with potential changes in operational parameters of the INL FB process and predict the resulting thermal history in the aluminum plates.

For computational efficiency, the current model assumes a simplified version of the actual process. In the actual process, two large aluminum plates clamped on a traversing table make several parallel passes under a rotating tool. The plates (now bonded together) are then flipped for the backside, or second side, to be welded. Excess material is sheared off of the ends and sides, leaving only the center part of the plate which contains the monolithic fuel. The model employs a simplified approach by assuming steady-state in the center part of the plate. The plunge and removal of the tool are not considered because affected areas of the plate are sheared-off and discarded after bonding, leaving only the steady-state portion of the bond.

In this paper, the model will be presented with an explanation of settings and the reasoning behind them. Experiments used for validation and verification of the model will also be presented, accompanied by their results. These results will be compared with the model output

in order to determine the extent to which the model accurately reflects the process.

2. Modeling

The model was developed using the COMSOL Multiphysics program produced by COMSOL, Inc. A multiphysics program was selected due to the necessity of considering interaction between material motion and heat generation in the finite element analysis. A stress-strain mode was also applied to the model to enable application of a friction-based heat equation dependent on distributed load.

2.1 Geometry

The model geometry includes three, three-dimensional pieces in a Cartesian coordinate system; a tool, an aluminum plate, and a steel anvil insert. The tool is comprised of a shoulder 38.1 mm in diameter and 7.14 mm high with a pin of diameter 15.9 mm extending down from the shoulder center 0.381 mm. The tool material is a proprietary tungsten-based alloy exhibiting good hardness and heat transfer properties. The model tool is true to the actual tool except that the model geometry does not include a recessed region around the pin or rounded edges. These features exist in the actual tool but are absent from the model because they were considered reasonable simplifications to avoid using an extremely fine mesh. The upper boundary of the tool is modeled with a heat sink equation to simulate loss of heat due to internal coolant flow.

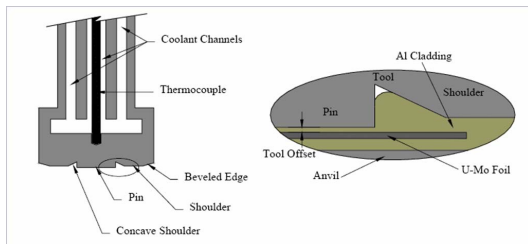


Figure 1. This tool schematic shows the internal coolant system [4].

The aluminum plate is modeled with dimensions that represent the combined thickness of two thinner plates. This plate is modeled as a continuum so only a small fraction of the actual plate size is included in the geometry. In this design, the tool is centered

toward one end of the plate piece to allow the cooling material to be modeled. The aluminum alloy used in the process and the model is 6061-T6.

The steel insert is the part of the anvil on which the plate sits during the weld. The modeled dimensions are 22.9 cm x 50.8 mm x 3.18 mm and is made of 4140 steel. This is the only part of the anvil modeled because it acts as a sufficient heat sink (when considered as a continuum) to create desired heat loss effect without over complication.

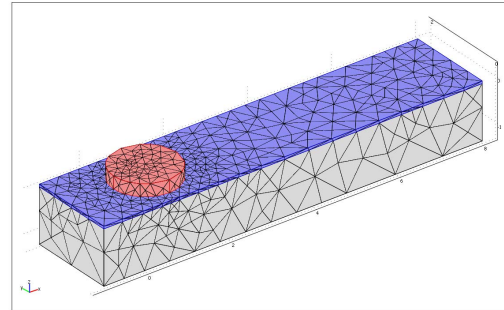


Figure 2. The tool is shown in red, the plate in blue, and the insert in gray.

One important measure that has tended toward complication is inclusion of material on both sides of the weld line. Many prior models have incorporated an assumption of symmetry across the weld line or around the tool face in order to simplify computation [7-10]. However, since the INL process involves successive passes that overlap one another, it is important to analyze differences between the advancing and retreating sides of the tool. In this way not only single passes can be modeled but also successive passes by simply changing the material properties on one side of the weld line to simulate the as-welded microstructure.

2.2 Equations

The model was constructed with the understanding that weld-speed, rotational speed, and applied load were the primary operational variables. These are connected to the model equations and are easy to change without affecting any other aspects of the model. Likewise, material properties and physical equations can be adjusted for changes in tool

material and different explanations of aluminum movement and heat generation.

The most significant equations for this model are associated with the aluminum movement and heat generated by the tool. Since the aluminum is treated as a continuum, the edges and bottom of the plate are assigned velocities equal to the traverse speed of the bond. This is accomplished using a Navier-Stokes fluid flow mode with designated boundary conditions. The rotation of the tool is modeled with two rotational velocity equations – one for the x -axis and one for the y -axis – applied to the boundaries between the tool face and aluminum plate:

$$\begin{aligned} \mathbf{u}_{\text{rot}} &= (-\Omega) \times (\mathbf{y} - \mathbf{y}_{\text{tool}}) \\ \mathbf{v}_{\text{rot}} &= (-\Omega) \times (\mathbf{x} - \mathbf{x}_{\text{tool}}) \end{aligned}$$

These equations generate x and y velocity vectors at every point (x,y) on the boundary dependent on the distance from the tool center $(x_{\text{tool}}, y_{\text{tool}})$. The resulting effect is a thin layer of aluminum rotating at the same speed (Ω) as the tool face. This motion dissipates into the bulk of the aluminum plate, which therefore has an internal velocity combining effects of the traverse speed and the rotation, given an assigned viscosity. For this model a reasonable viscosity estimate of $1 \times 10^5 \text{ Pa}\cdot\text{s}$ is used [6]. However since the material should soften as higher temperatures are achieved, future efforts will incorporate temperature-dependent viscosity functions.

In addition to the aluminum under the tool, the tool itself must also spin in order to accurately reflect the process. In this case it is unnecessary to give the tool physical rotation because only the heat transfer is of interest. For this reason, rotation was simplified into a pseudo-convection using the same velocity equations. Employing COMSOL's convection option, rather than causing physical rotation, simplified the process and achieved the effect of a spinning tool for heat transfer.

Prior literature has suggested that a heat generation equation based on either friction [7, 8, 10] or viscous dissipation [9, 12] could accurately represent the stir weld process. A friction-based equation was adapted from Frigaard et al. [7] and is used in this model for the shoulder and pin faces:

$$q_{\text{face}} = (\mu \times \sigma_z) \times (\Omega \times \sqrt{(x - x_{\text{tool}})^2 + (y - y_{\text{tool}})^2})$$

The first quantity in the equation represents the frictional force over the area of the tool face. The z -direction stress on the tool-plate boundary is calculated by the program from an applied load of 44.5 kN on the top of the tool. This technique allows load to be distributed appropriately at the surface according to tool geometry. The friction coefficient is adjusted in order to calibrate the model. A value of 0.85 best reflects the experimental data and is within the wide range of published values (0.4-1) [6, 10]. The second quantity in the equation gives the magnitude of the aluminum velocity and could also be defined in terms of the u_{rot} and v_{rot} expressions previously established. A similar equation in which stress is drawn from the x and y -axes governs heat generated by the sides of the pin. The heat contribution of the sides in the model is minimal, however.

In addition to generating heat due to friction, this tool design also removes heat through an internal coolant system. The system is modeled with a heat sink equation placed on the upper boundary of the tool. The quantity of heat removed was estimated from the coolant inlet and outlet temperatures and flow rate to be 790 W.

This model can be solved as either time-dependent or steady-state. A near-steady state condition is reached rapidly in the time-dependent solution and should accurately reflect the conditions in the middle of the bond. Considering that the initial plunge area and some of the nearby bond are sheared from the plate before it is used, much of the initial non-steady-state bond is inconsequential.

3. Experiment/Validation/Calibration

In order to validate the model it was necessary to measure temperatures at multiple points in close proximity under the tool. If positioned properly, a group of thermocouples would give a temperature under the advancing side, the pin, and the retreating side. It would then be possible to validate or calibrate the model by comparing thermocouple readings from an experimental bond to model output.

Such a validation experiment was designed and executed. Three thermocouples were placed

between two aluminum sheets under a stainless steel “surrogate” foil in parallel channels, each a half inch apart. The thermocouples were set with different lengths into the material such that their tips formed a diagonal line across part of the plate. Temperatures were recorded for six passes on the original upper side and five on the opposite side. The experiment yielded temperature data that were used to validate and calibrate the model.

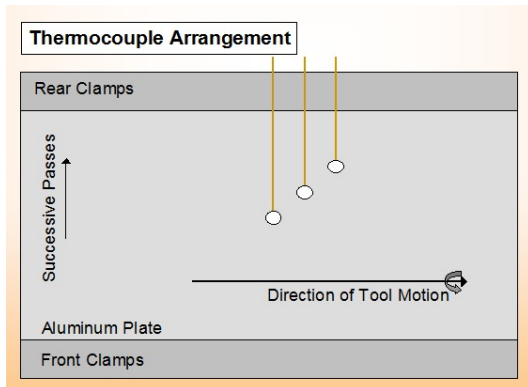


Figure 3. Thermocouple arrangement for the validation experiment – the tool approaches from the left and rotates in a counterclockwise direction.

4. Results:

Though the model calibration has not yet been verified, certain initial observations can be made as to the shape of the aluminum thermal history curve. These general observations give a good indication of the accuracy of the model, as the calibration should only affect the magnitude of the temperatures - not the shape of the curve.

The first such observation relates to the temperature curve as a whole. A comparison of the curve to experimental data shows the same steep temperature gradient at the front shoulder and a slow cooling after the tool has passed. The steady state situation allows a time-temperature plot to be correlated to a displacement-temperature plot using the traverse speed. As seen in Figure 4, the front edge of the shoulder is defined as a displacement of zero. The material can be seen to heat up from an initial temperature, reach a peak under the tool, and cool gradually. This resembles the thermocouple data from the validation and calibration experiment, also shown in Figure 4.

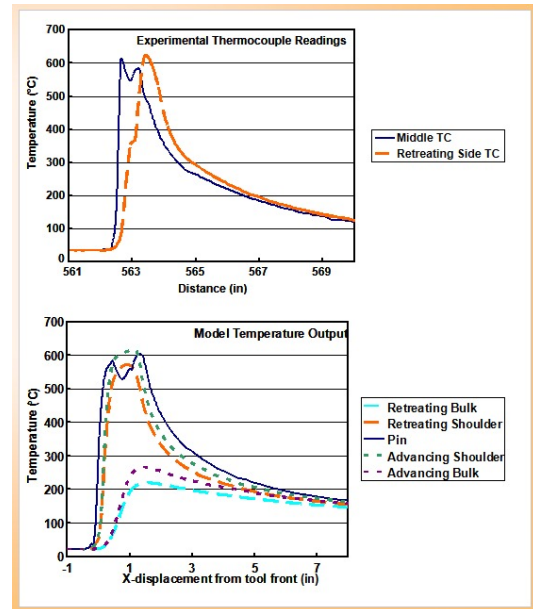


Figure 4. Experimental thermocouple readings as a function of plate distance and thermal model results as a function of tool displacement.

The second significant observation specifically deals with the material directly under the pin. The model indicates that this material is colder than the surrounding aluminum by approximately 64°C . This suggests that aluminum directly under the pin is effectively trapped in this slow-moving region. Impressively, data from the validation experiment also shows a drop in temperature as the thermocouples pass under the pin. Discovery of this phenomenon both supports the model and hints at the effect of the pin in the bonding process.

The final major observation concerns the difference between the advancing and retreating sides of the tool. As the tool rotates, the advancing side is forced in opposition to the new plate material while the retreating side moves in the same direction as the plate. The advancing side is moving into cold material, however, while the retreating side is transporting some aluminum that is already hot. The result is an asymmetrical temperature distribution across the bond centerline but the phenomena give no apparent indication as to which side is hotter. Visual observation of the back side of a single-pass bond revealed a shift in the bond position toward the advancing side. This side should therefore exhibit a higher temperature than the

retreating side in order for the bond to form farther from the tool center. The model shows a higher temperature on the advancing side, agreeing with this interpretation of the bond shift. Both of these observations are presented graphically in Figure 5.

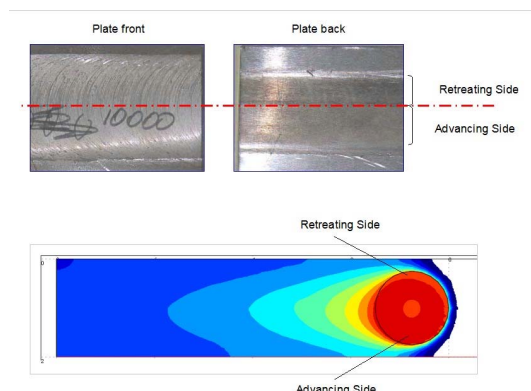


Figure 5. Photographs of a FB plate top side (left) and bottom side (right) showing a shift in the bond line are presented at the top. At the bottom, a thermal history profile of the tool and surrounding material shows the pin and retreating edge are cooler than the advancing edge, confirming the experimental observation.

5. Future work:

Future work on this model will include both general calibration of the settings and equations and the pursuit of more specific improvements. Certain elements of interest appeared during the development of this model that could improve its accuracy, but are thus far beyond its scope. Among these are a temperature-dependent viscosity and modeling of successive passes.

A temperature-dependent viscosity would simulate the softening of the aluminum as it approaches the melting point. While there are data available for the mechanical properties of aluminum with respect to temperature, this must be converted to a viscosity function that will work within the model framework.

Though the actual FB process involves multiple passes, the model does not yet consider adjustments for successive passes after the first. This was always understood as the eventual goal of the model so preparation has been made for successive passes. Future work in this area will include dividing the model geometry into an overlapping, welded area and a fresh area of the plate. Material properties can then be changed in

the already-welded, overlapping area to account for the affected microstructure.

In addition to work improving the model, experimental work will continue on the FB process. In this way the model's value as a predictive tool can be assessed as more experimental data are gathered for comparison.

6. Conclusions:

A three-dimensional thermal model was developed for the INL's unique friction bonding process. Model output plots reflect the shapes of experimental temperature results, including a cool area under the pin and a high temperature on the advancing side of the tool.

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